RHIC Accelerator
Achievements and Planned Upgrades

RHIC overview

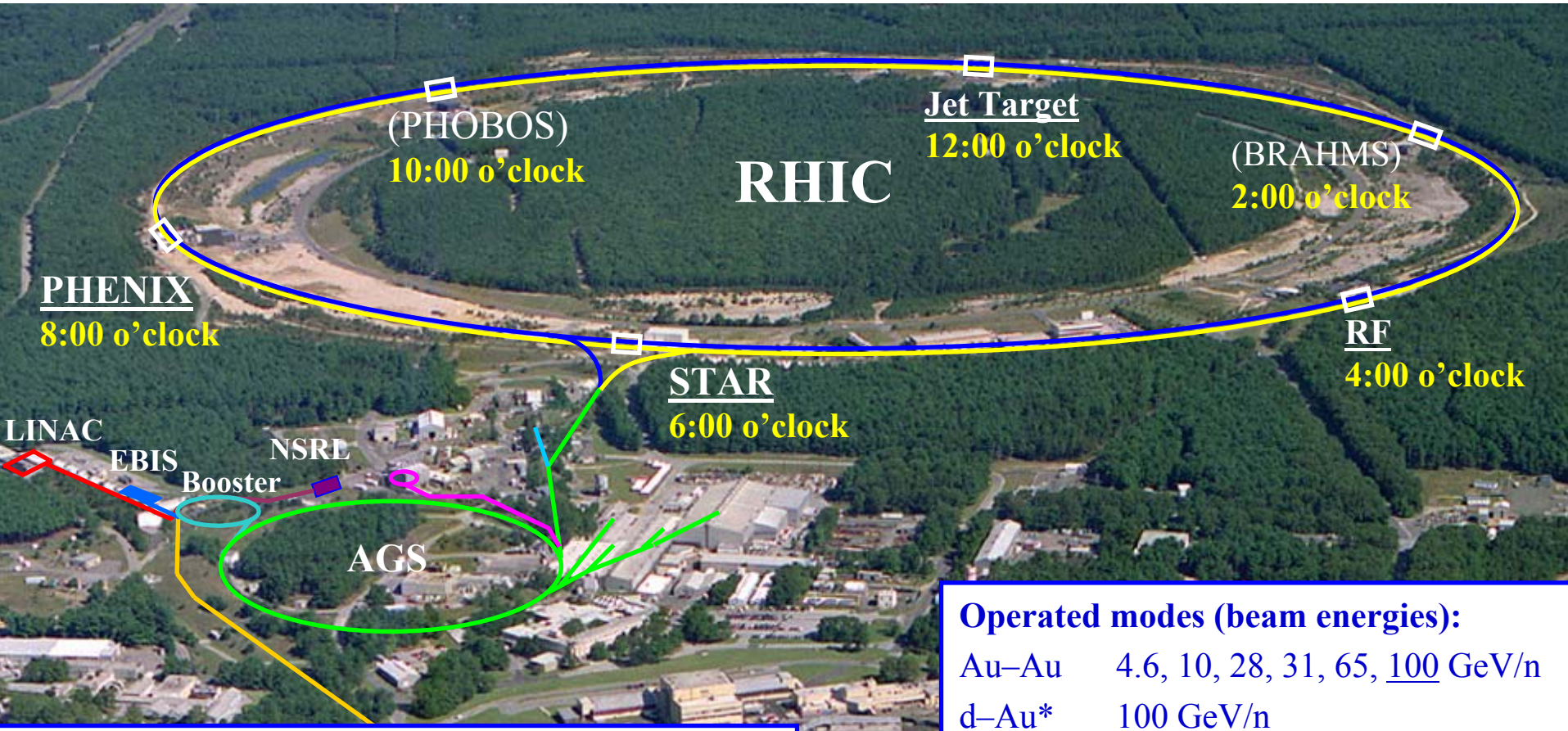
Luminosity and polarization evolution

Future upgrade path

BROOKHAVEN NATIONAL LABORATORY

Thomas Roser
AGS & RHIC Annual Users' Meeting
May 28, 2008

RHIC – a High Luminosity (Polarized) Hadron Collider



Achieved peak luminosities (100 GeV, nucl.-pair):

Au–Au	120×10^{30} cm^{-2} s^{-1}
p↑–p↑	35×10^{30} cm^{-2} s^{-1}

Other large hadron colliders (scaled to 100 GeV):

Tevatron (p – pbar)	32×10^{30} cm^{-2} s^{-1}
LHC (p – p, design)	140×10^{30} cm^{-2} s^{-1}

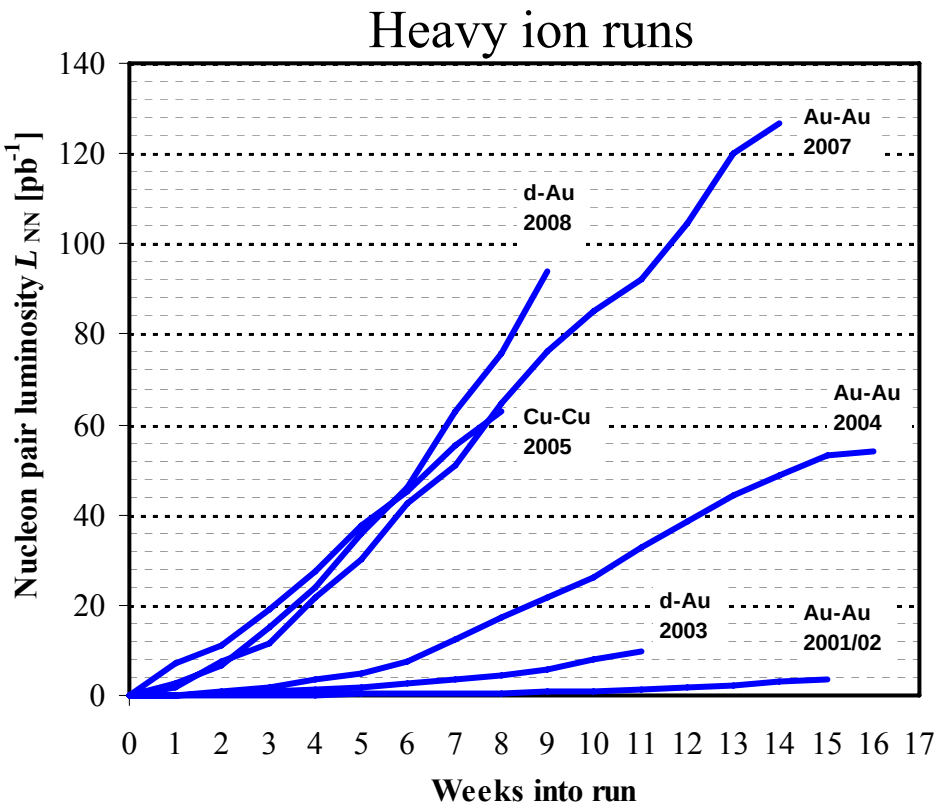
Operated modes (beam energies):

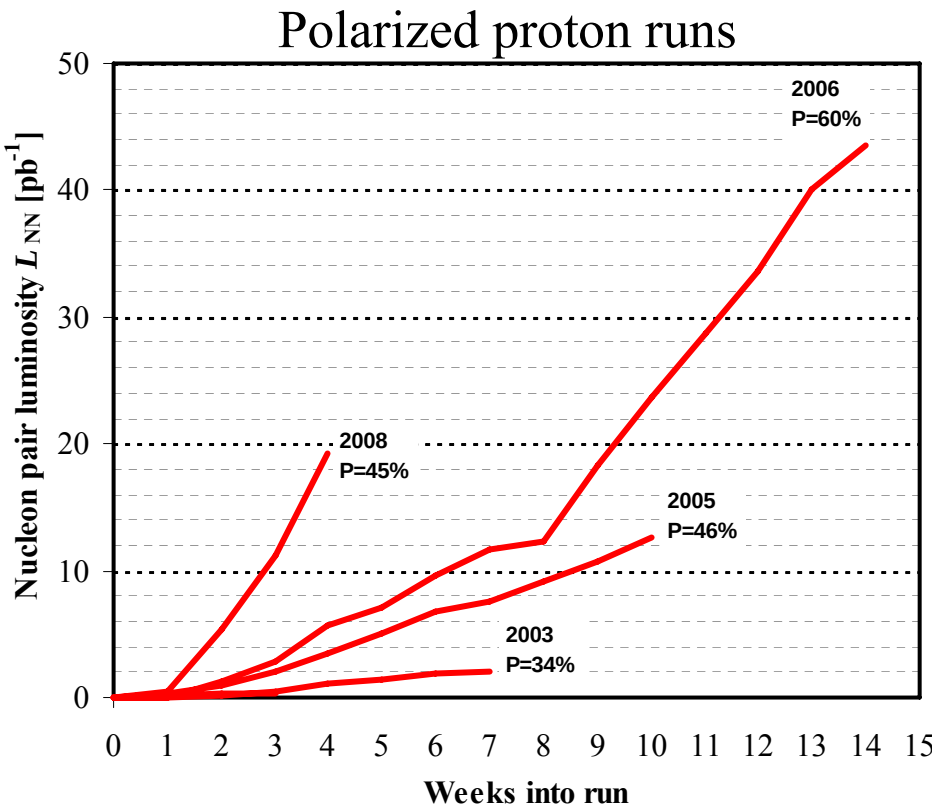
Au–Au	4.6, 10, 28, 31, 65, 100 GeV/n
d–Au*	100 GeV/n
Cu–Cu	11, 31, 100 GeV/n
p↑–p↑	11, 31, 100, 205, 250 GeV

Possible future modes:

Au – Au	2.5 GeV/n (AGS, SPS c.m. energy)
p↑ – Au*	100 GeV/n (*asymmetric rigidity)

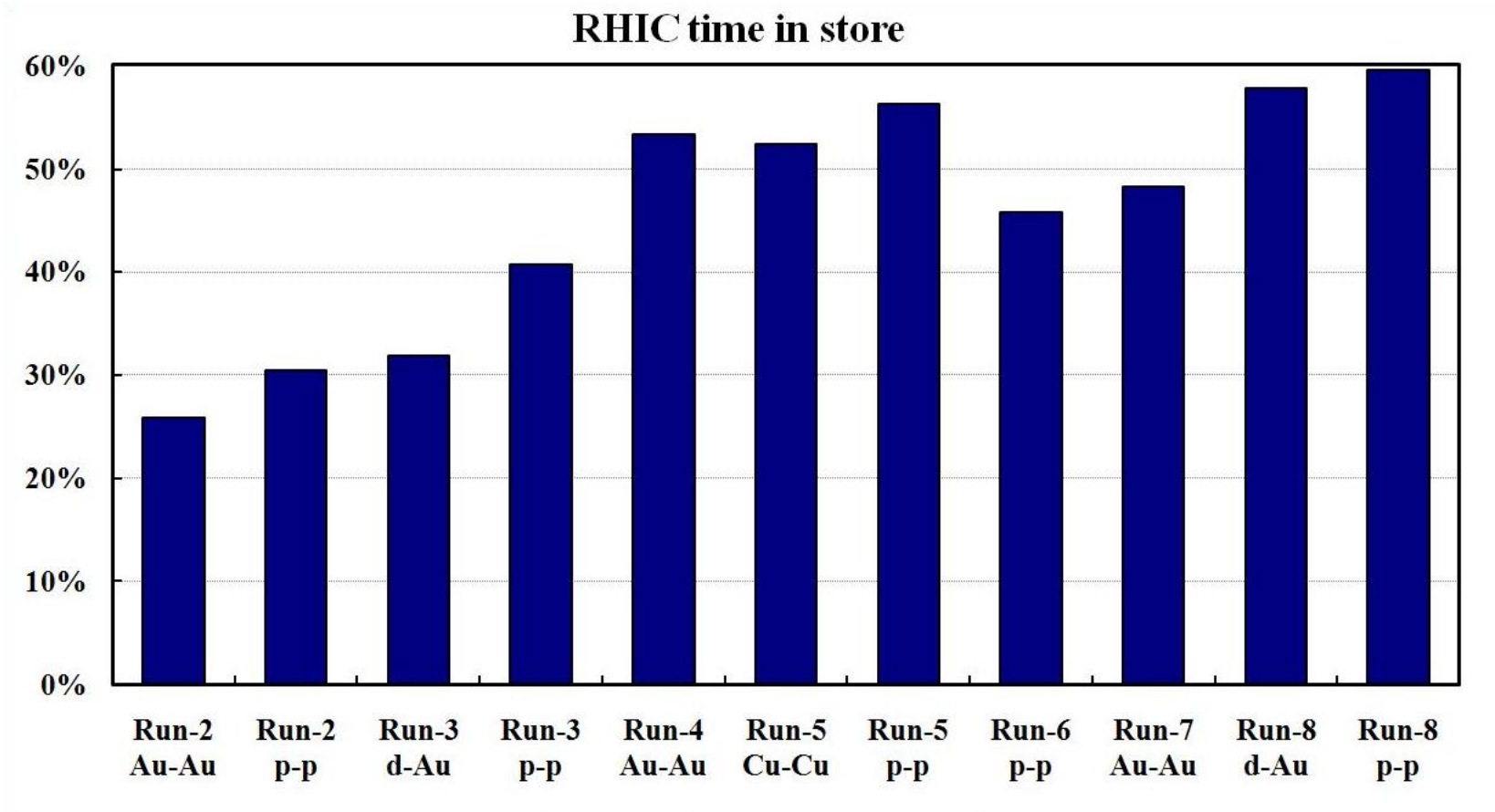
Delivered Luminosity and Polarization





Nucleon-pair luminosity: luminosity calculated with nucleons of nuclei treated independently; allows comparison of luminosities of different species; appropriate quantity for comparison runs.

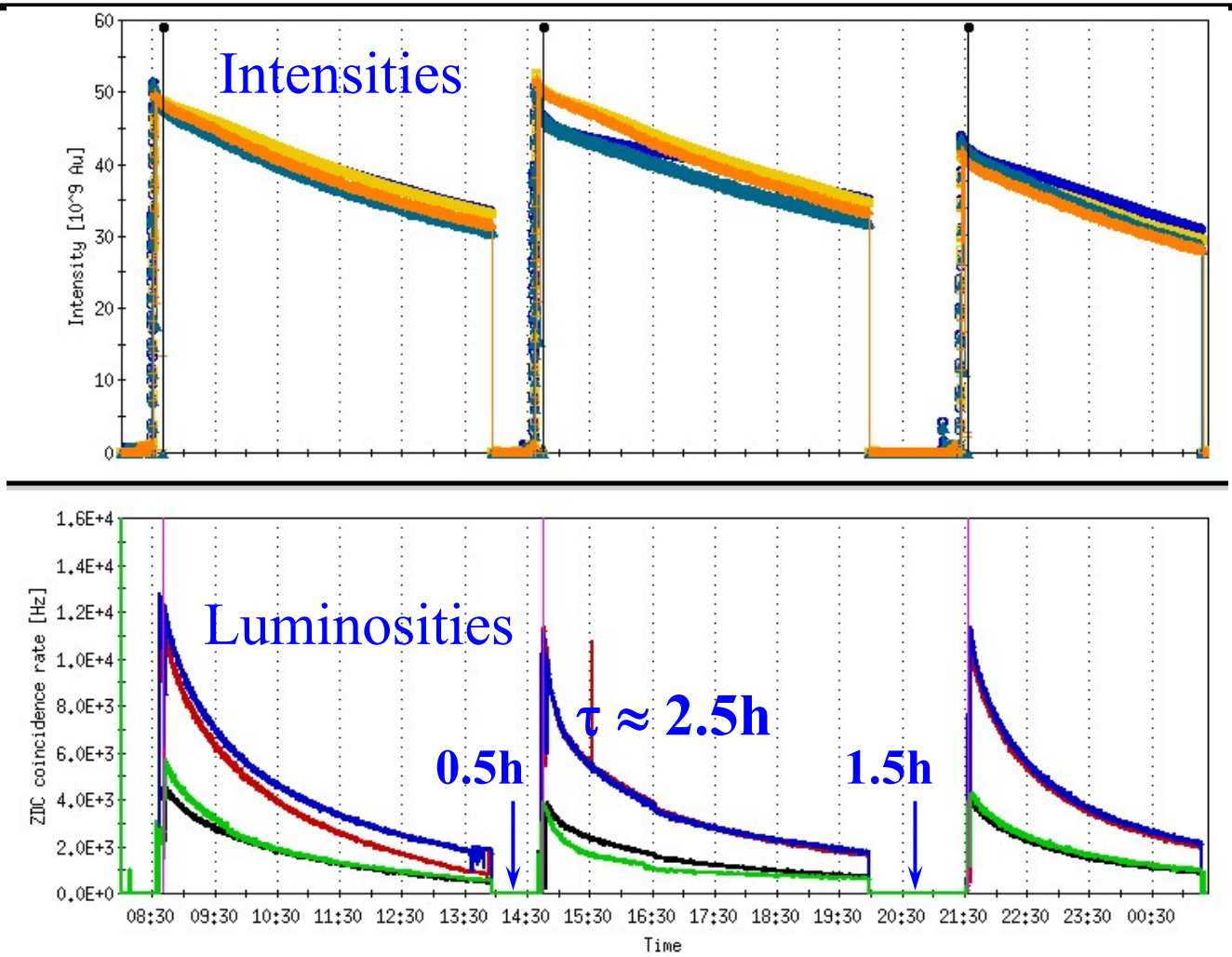
Calendar Time in Store



RHIC luminosity and polarization goals

Parameter	unit	**Achieved**	**Enhanced design**	**Next Lumi upgrade**
Au-Au operation		**(2007)**		**(~ 2011)**
Energy	GeV/nucleon	100	100	100
No of bunches	…	103	111	111
Bunch intensity	10^9	1.1	1.0	1.0
Average Luminosity	**10^{26}cm^{-2}s^{-1}**	**12**	**8**	**40**
p↑- p↑ operation		**(2006/08)**	**(~ 2010)**	**(~ 2012)**
Energy	GeV	100	100 (250)	250
No of bunches	…	111	111	111
Bunch intensity	10^{11}	1.5	2.0	2.0
Average Luminosity	**10^{30}cm^{-2}s^{-1}**	**23**	**60 (150)**	**300**
Polarization	**%**	**60**	**70**	**70**

Luminosity Limit – Intra-Beam Scattering (IBS)



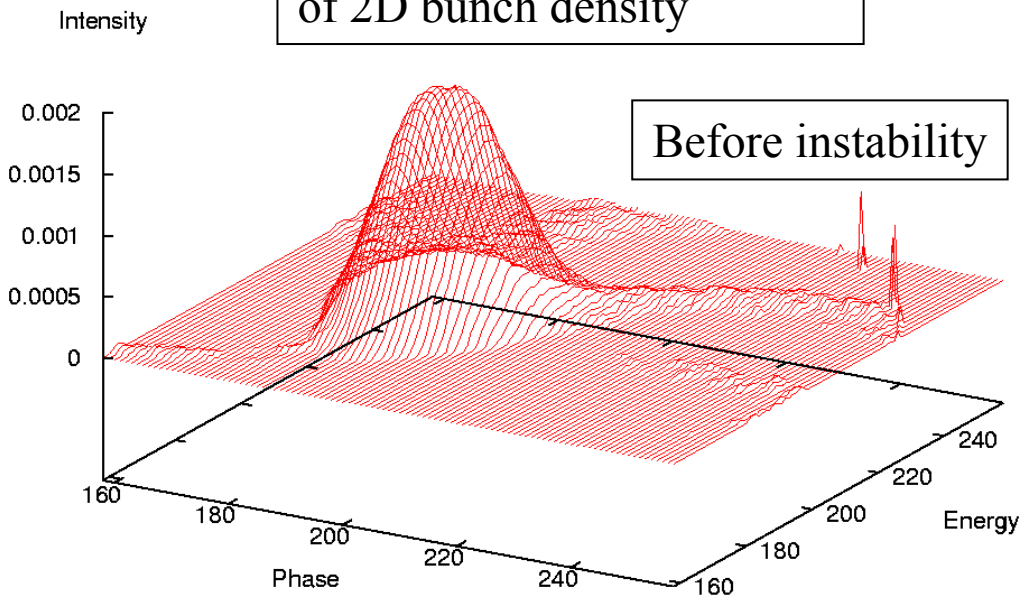
- Debunching requires continuous gap cleaning
- Luminosity lifetime requires frequent refills
- Increased focusing decreased IBS ("IBS suppression" lattice)
- Cooling at full energy: stochastic and electron cooling

BROOKHAVEN NATIONAL LABORATORY

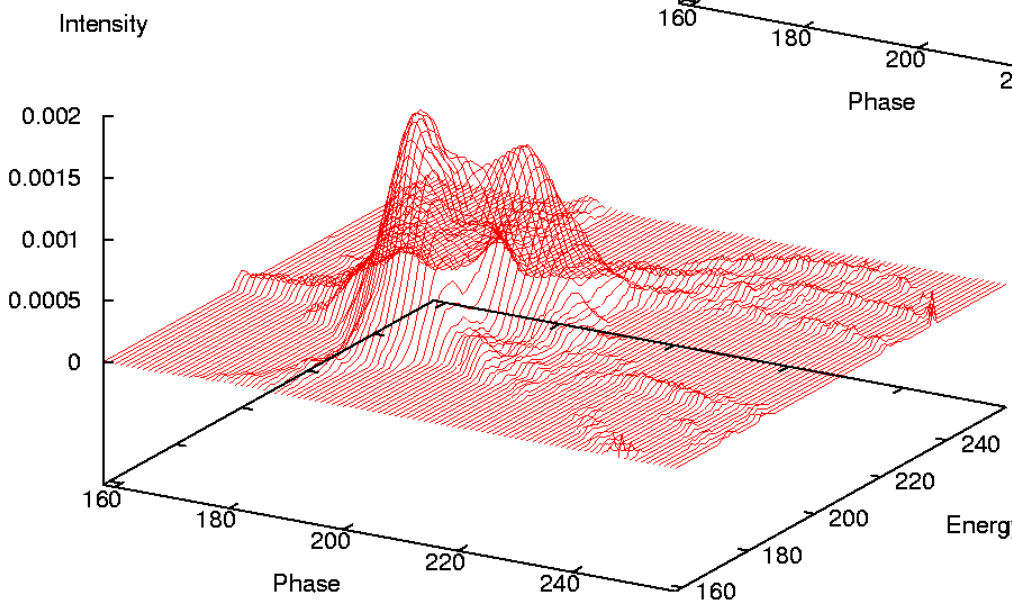
Luminosity Limit – Fast Instability Near Transition

- Fast transverse instability (~ GHz)
- High sensitivity around transition (high peak current, zero chromaticity)
- Effect of broadband impedance and electron clouds
- Cures: octupoles, suppress electron clouds, chromaticity jump, active damper (?)

Tomographic reconstruction of 2D bunch density



Before instability



After instability with ~ 10 ms growth rate

Upgrades for heavy ion luminosity (Au-Au)

Main limits: IBS, transition instabilities

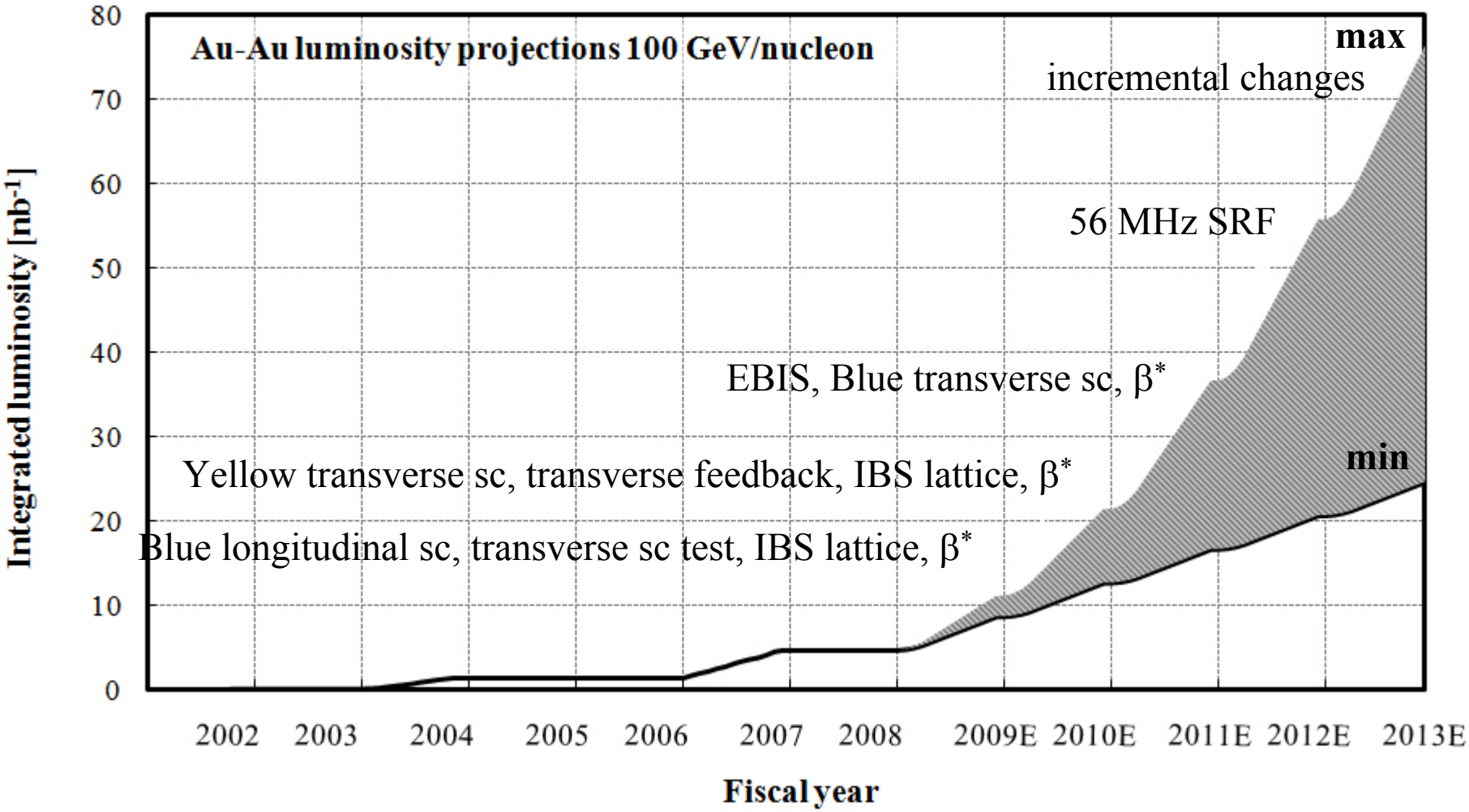
potential luminosity gains
(not all independent, cannot simply multiply)

- Reduction in β* from 80cm to 50cm (+ 60%)
- Lattice with reduced IBS (+ 25%)
- Blue longitudinal stochastic cooling (+ 15%)
- Transverse stochastic cooling (+ 400%)
- Transverse damper / scrubbing (+ 40%)
  (avoid beam emittance growth from transverse instability at transition)
- 56MHz SRF (+ 40%)
  (eliminates satellite bunches, shorter vertex distribution)
- EBIS, begin commissioning in FY10↑ (reliability, U, ^{3}He↑)

5-year projections Au-Au

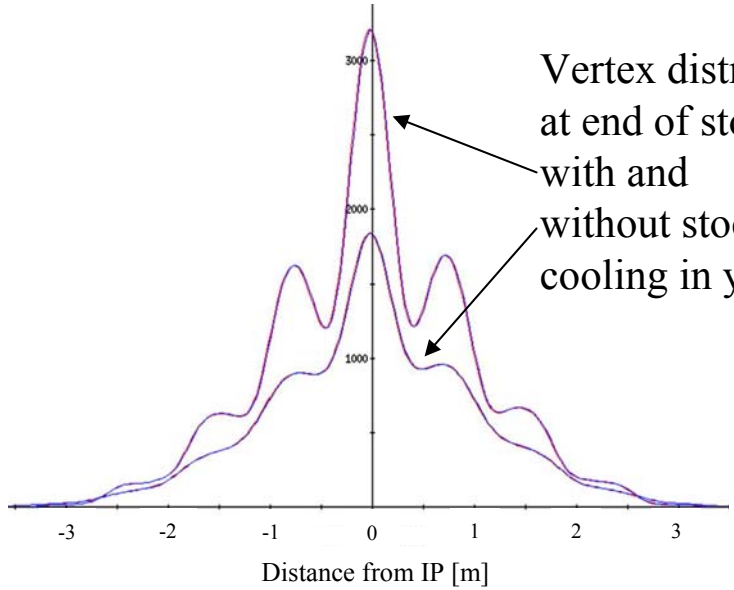
5-year projections for Au-Au luminosity assuming 12 weeks of physics in every year

min: no performance increase max: success of all major upgrade projects



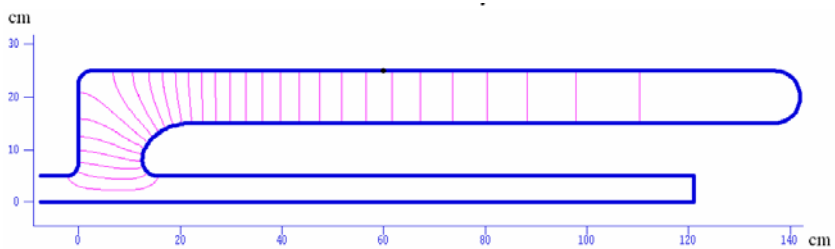
Stochastic Cooling and 56 MHz SRF cavity

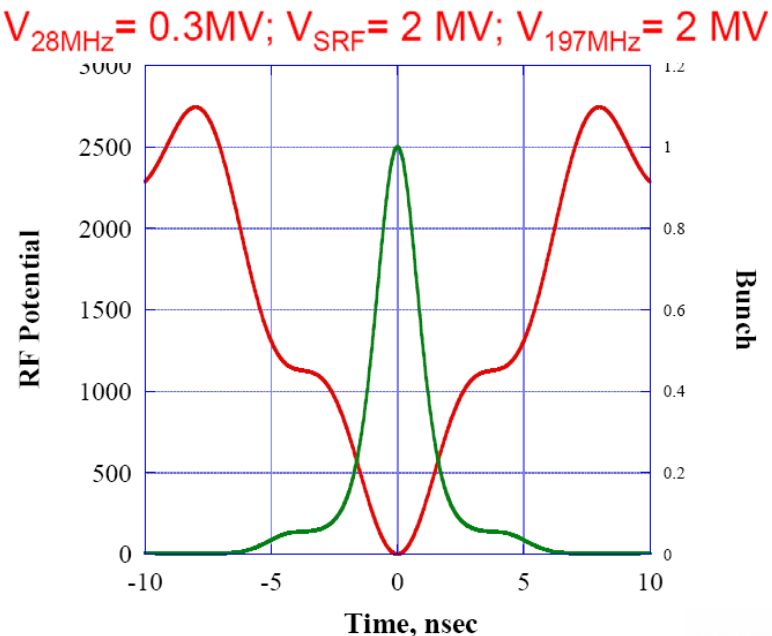
- Longitudinal bunched beam stochastic cooling demonstrated at 100 GeV/n in RHIC counteracting longitudinal IBS.
- Longitudinal stochastic cooling in Blue ring under construction



56 MHz SRF storage cavity:

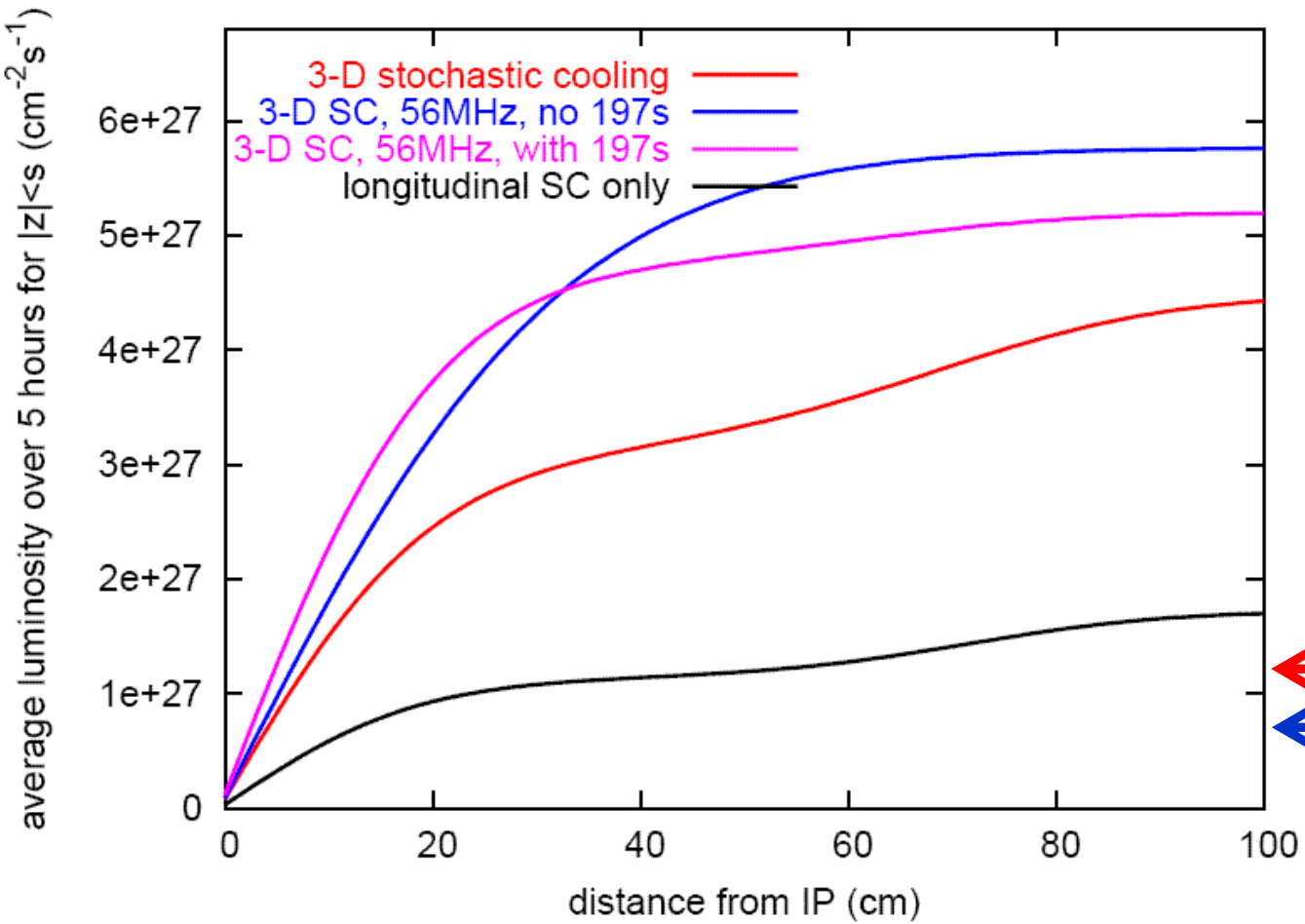
- Avoid rebucketing operation.
- Greatly reduces satellite bunches
- Quarter wave resonator





BROOKHAVEN NATIONAL LABORATORY

Stochastic cooling & 56 MHz SRF – luminosity increase

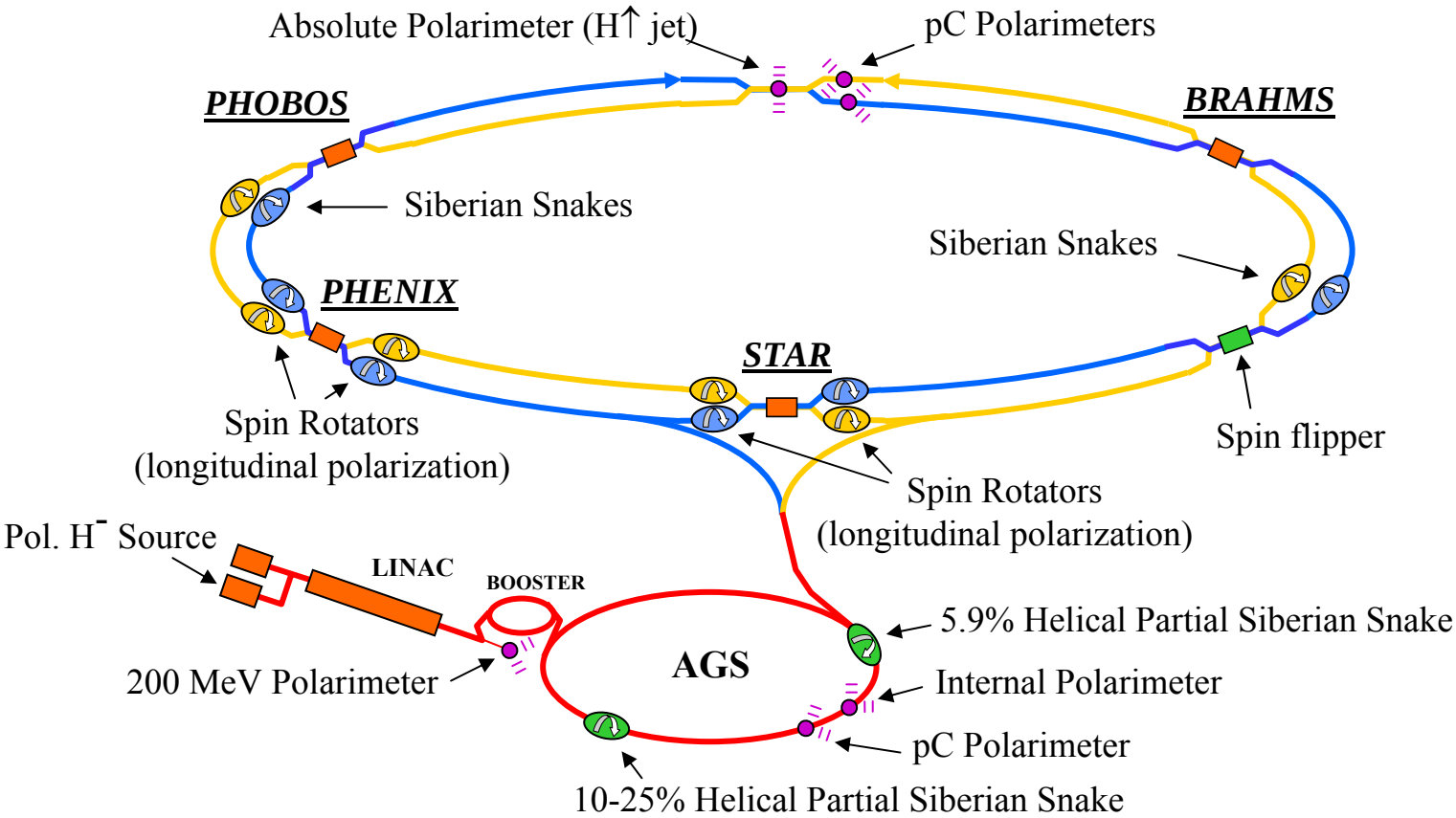


Achieved in Run-7 Yellow longitudinal stochastic cooling only.

RHIC enhanced design

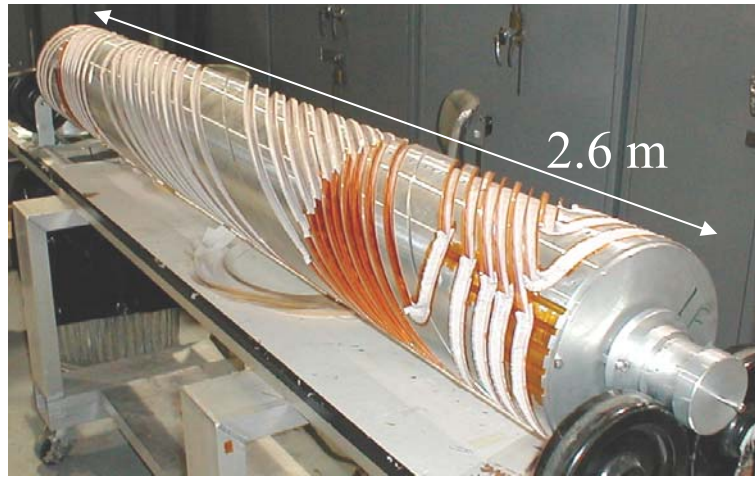
Calculation by M. Blaskiewicz.

RHIC – First Polarized Hadron Collider



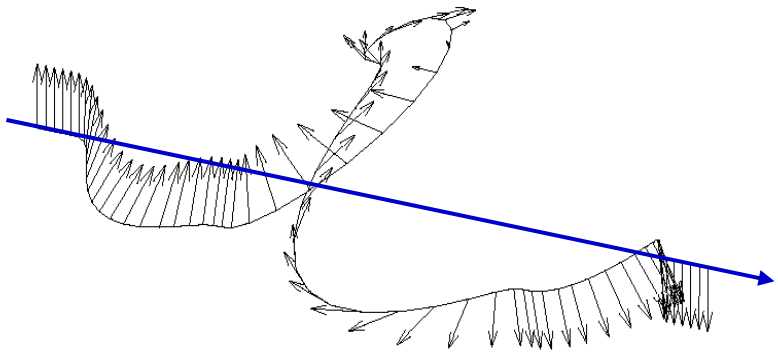
Without Siberian snakes: $\nu_{sp} = G\gamma = 1.79$ E/m → ~1000 depolarizing resonances
With Siberian snakes (local 180° spin rotators): $\nu_{sp} = ½$ → no first order resonances
Two partial Siberian snakes (11° and 27° spin rotators) in AGS

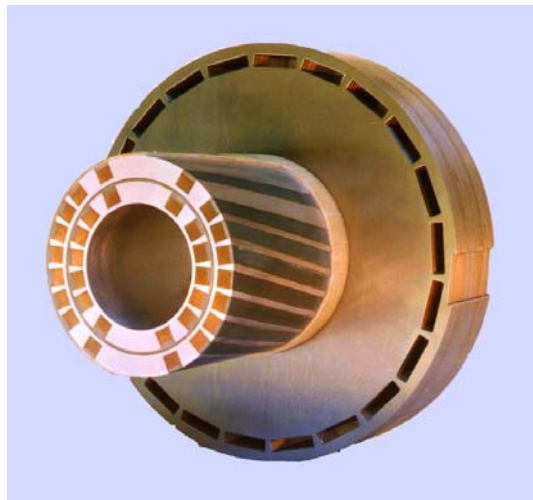
Siberian Snakes



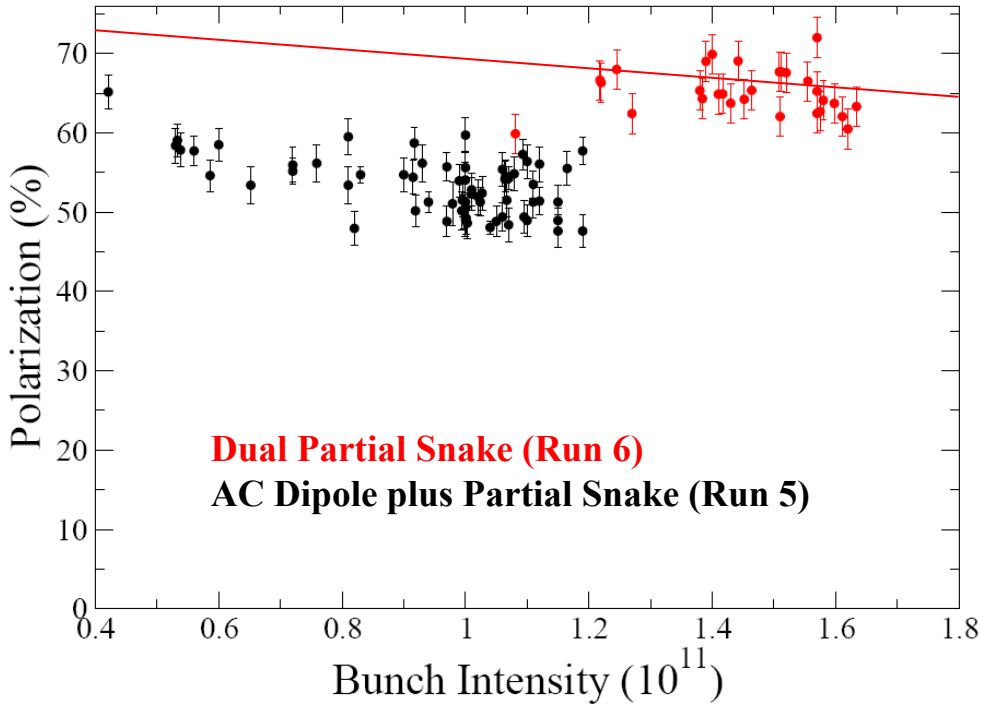
Major funding by RIKEN, Japan
RT helical dipole constructed at Tokano Ind., Japan
SC helical dipoles constructed at BNL

AGS Siberian Snakes: variable twist helical dipoles, 1.5 T (RT) and 3 T (SC), 2.6 m
RHIC Siberian Snakes: 4 SC helical dipoles, 4 T, each 2.4 m long and full 360° twist



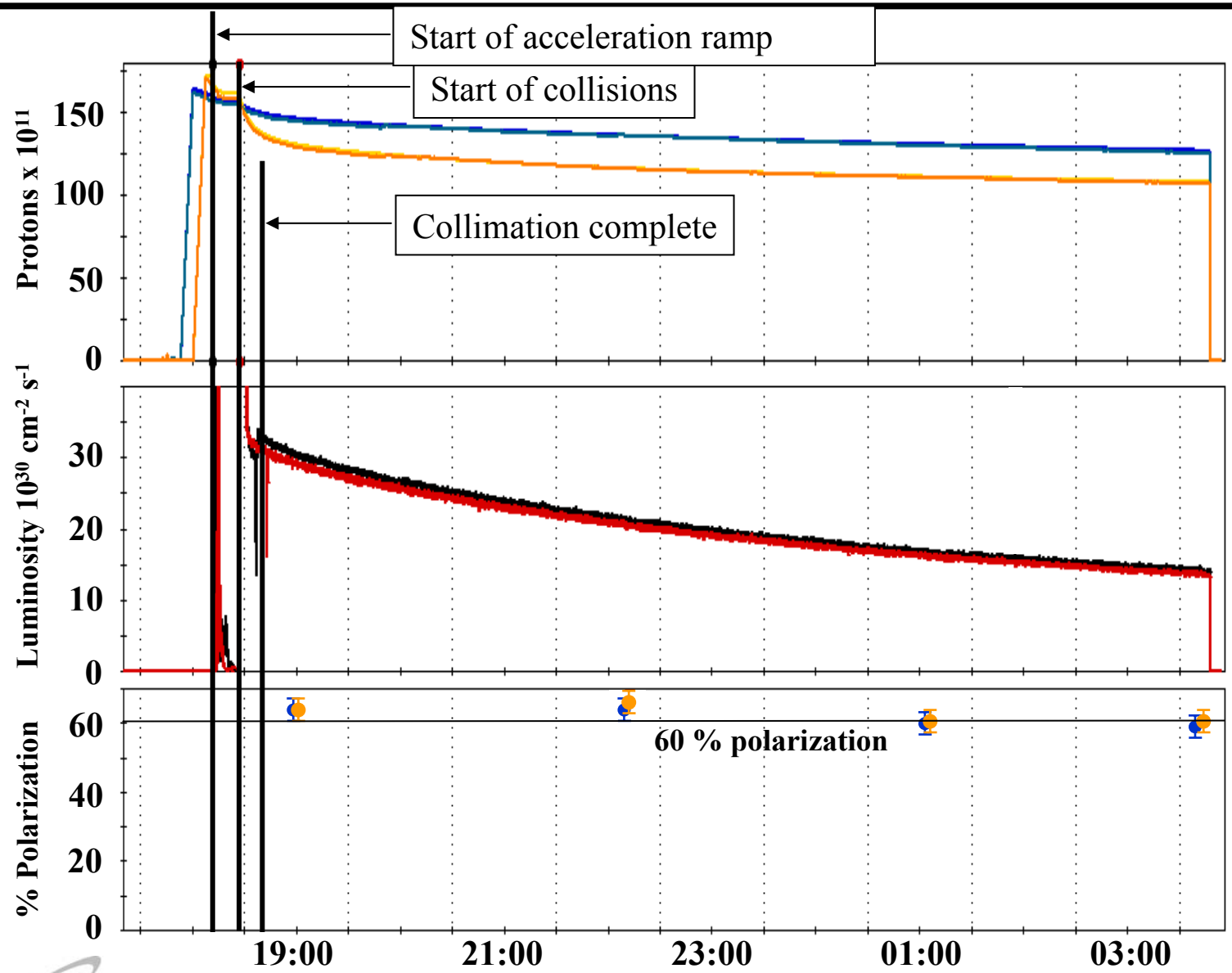


AGS Polarization



- Dual Partial Snake in AGS avoided depolarization from all vertical depolarizing resonances. Strong partial snakes also drive weak horizontal depol. resonances. (~ 5-10% polarization loss)
- Plan to use tune jump for horizontal resonances

Luminosity and Polarization Lifetimes in RHIC at 100 GeV



BROOKHAVEN NATIONAL LABORATORY

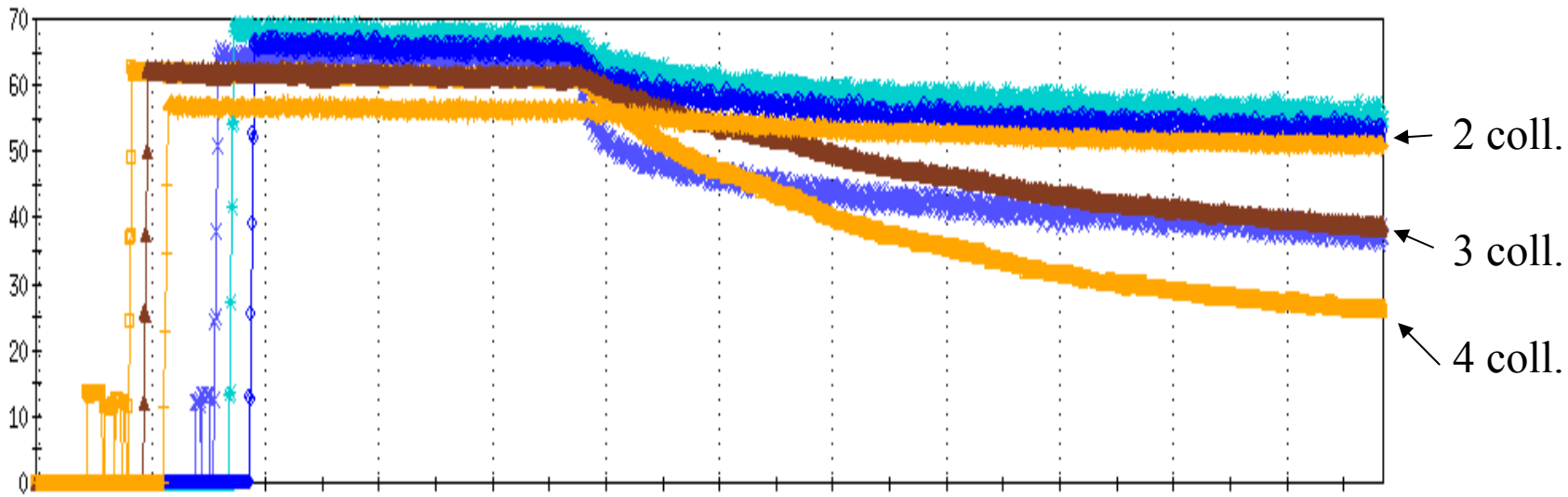
45 % polarization on first acceleration to 250 GeV!

Run-7 and Run-8 p↑-p↑ operation – polarization

- Source
  - P = 80 - 82% in Run-8 after 85 - 89% in Run-7
  - Aim for P = 85% in Run-9
- AGS
  - Tested stronger snake and near integer horizontal tune in Run-7
  - Tested injection on the fly (no flat bottom) in Run-8
  - In both cases significant intensity dependent polarization
  - Returned to Run-6 setup with P = 55% at extraction vs. P = 65% in Run-6 (half of the loss due to source, other half due to only 10 days of tuning)
  - For Run-9 use Run-6 set-up with tune jump for horizontal resonances
- RHIC
  - About 10% (absolute) lower P than in Run-6, more problems in Yellow
  - Learned that horizontal orbit angle through snakes needs better control
  - Need RHIC pC CNI polarimeter upgrade for better reliability

Luminosity Limit – Beam-Beam Tune Shift and Spread

- First strong-strong hadron collider (after ISR)
- Limits high luminosity pp operation
- Cures: Non-linear (chromaticity) corrections, better working point, electron lens



Upgrades for polarized protons

Main limits: beam-beam, p↑-operation

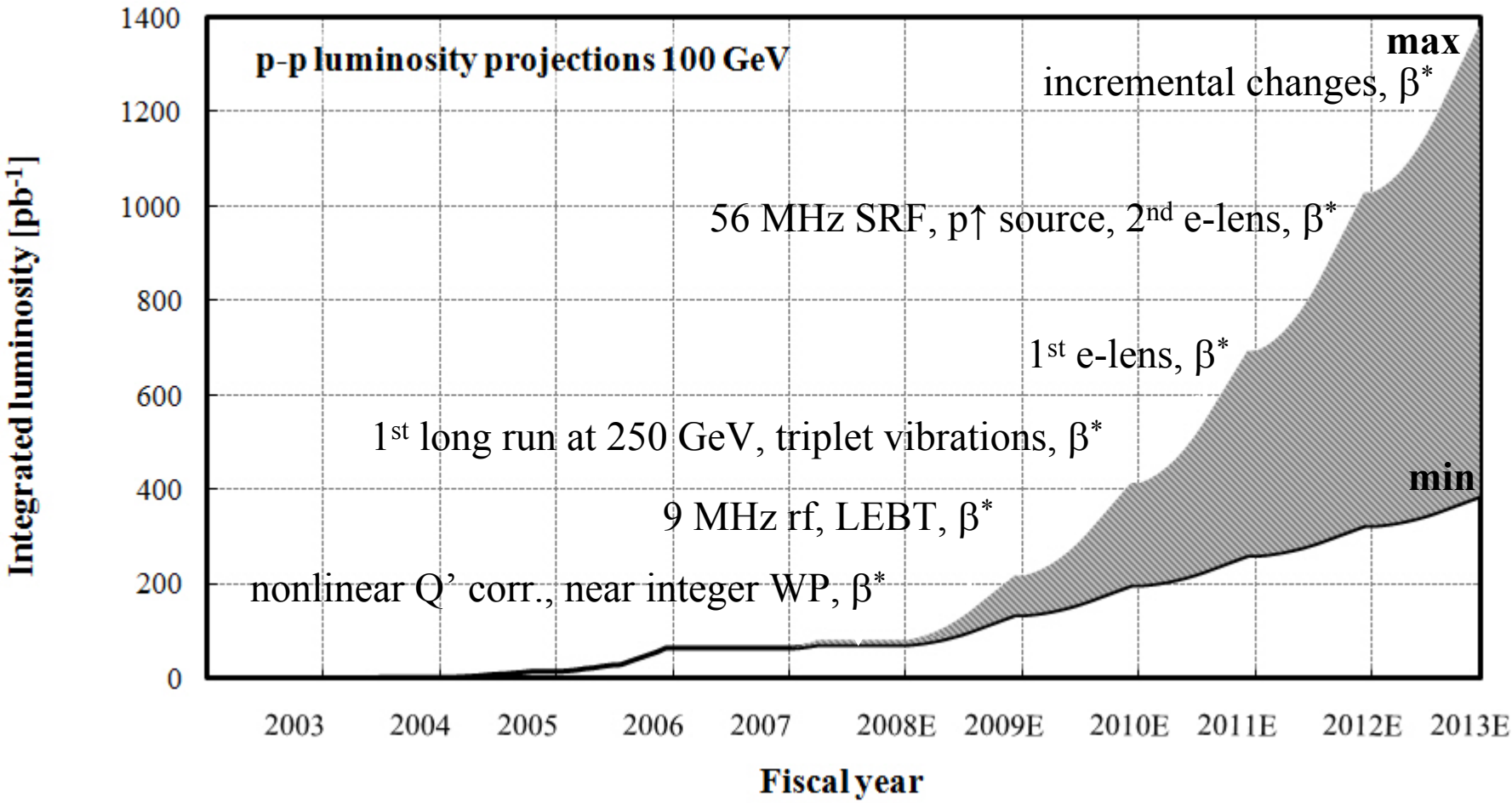
- Reduction in β* from 100cm to 50cm (+ 70% at σ_s=1m)
- Nonlinear chromaticity correction (+ 30%)
- LEBT/MEBT/Booster modifications for p↑ (+ 20%)
- 9 MHz cavity (+ 25% at β* = 1m, shorter vertex)
- Horizontal tune jumps in AGS (P + 5% absolute)
- Horizontal orbit control in RHIC snakes (avoids P loss in RHIC)
- Mitigate 10 Hz triplet vibration (+ 5 - 10%)
  (passive or active stabilization of cold masses, removal of driving term, orbit feedback)
- Near integer working point (+ 40%)
  (requires mitigation of 10 Hz triplet vibrations)
- 56 MHz cavity (operational flexibility, shorter vertex)
- R&D items:
  - Spin flipper
  - Electron lens
  - Coherent electron cooling

potential luminosity gains
(not all independent, cannot simply multiply)

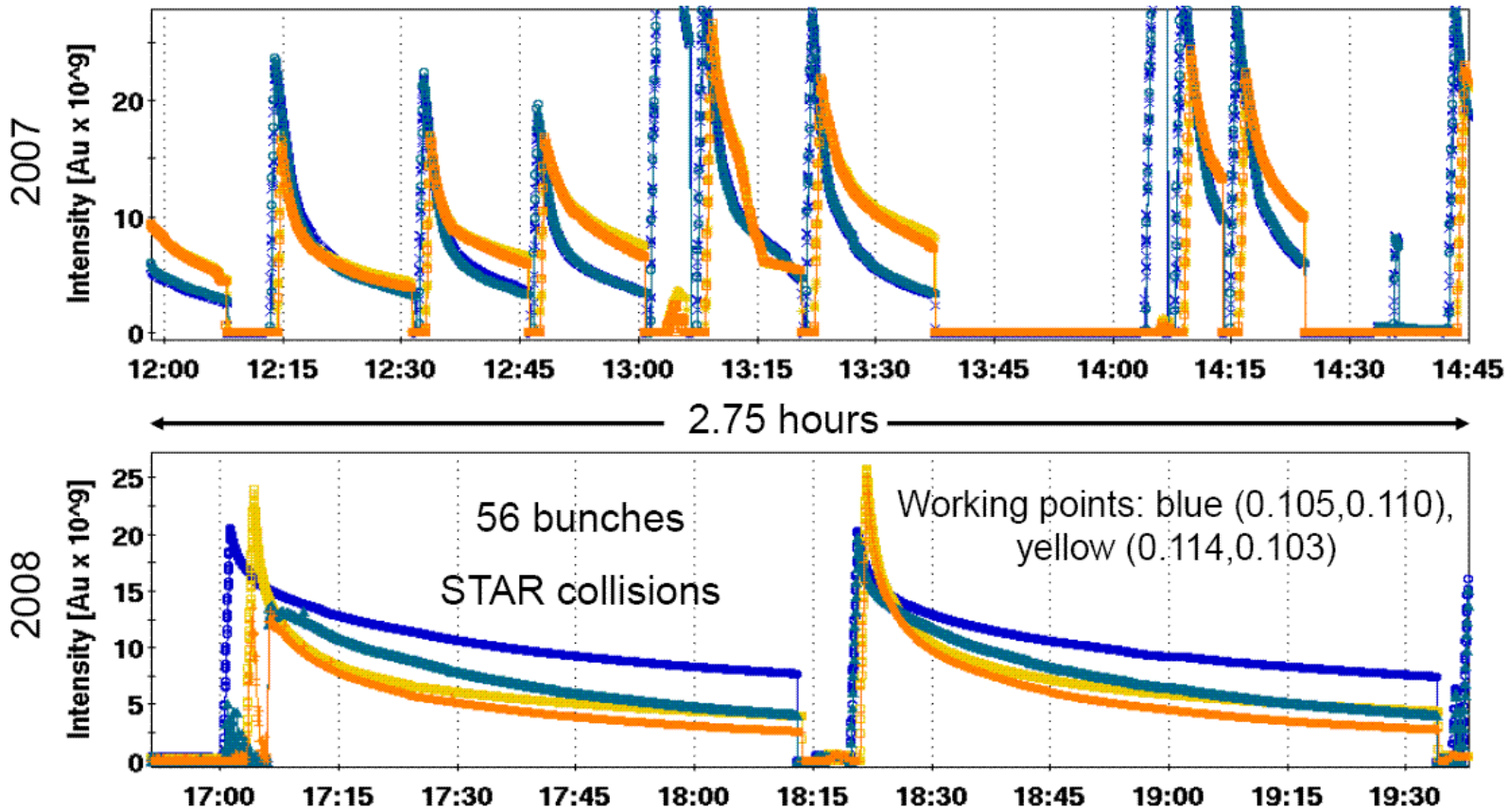
5-year projections p↑-p↑

5-year projections for p↑-p↑ luminosity assuming 12 weeks of physics in every year

min: no performance increase max: success of all major upgrade projects



Tests of √s = 9 GeV Au - Au operation in RHIC

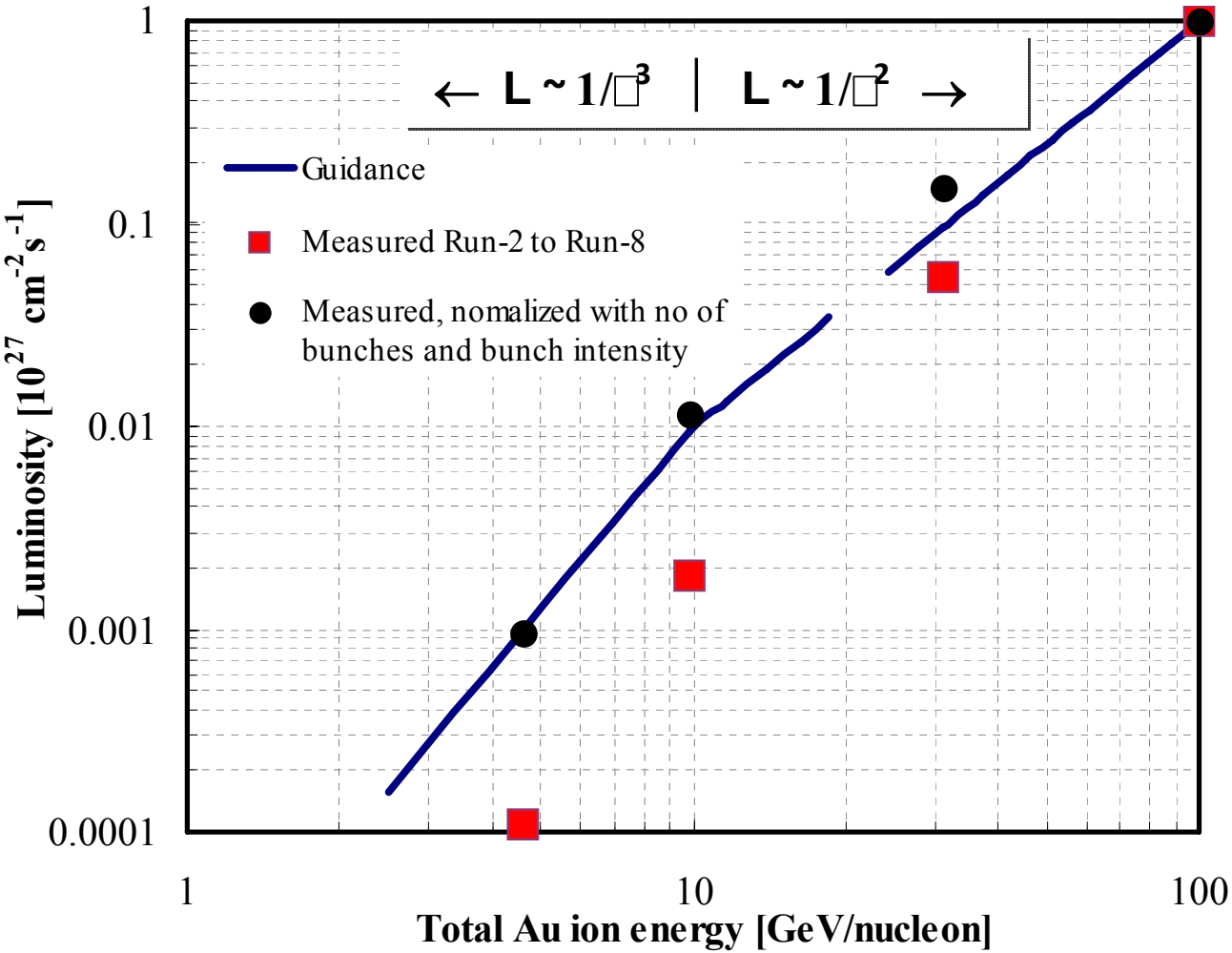


- 2008 blue beam lifetime: 3.5 minutes (fast), 50 minutes (slow)
- Sextupole reversal and elimination of octupoles clearly helped beam lifetime
- Injection efficiency and yellow beam lifetime can clearly benefit from further tuning

BROOKHAVEN NATIONAL LABORATORY

[T. Satogata, RHIC Retreat 2008]

Luminosity scaling with energy



Low energy Au-Au operation – Luminosity upgrade options

E-cooling in RHIC

- Luminosity limited by space charge (space charge limit $\Delta Q_{sc} = 0.05$)
- Expect 3-6 more luminosity when operating at space charge limit [A. Fedotov et al., C-A/AP/307]
- Electron cooling either with dc beam (Fermilab Pelletron) or with rf beam (56 MHz SRF gun, 703 SRF gun – under construction)

Top-off mode

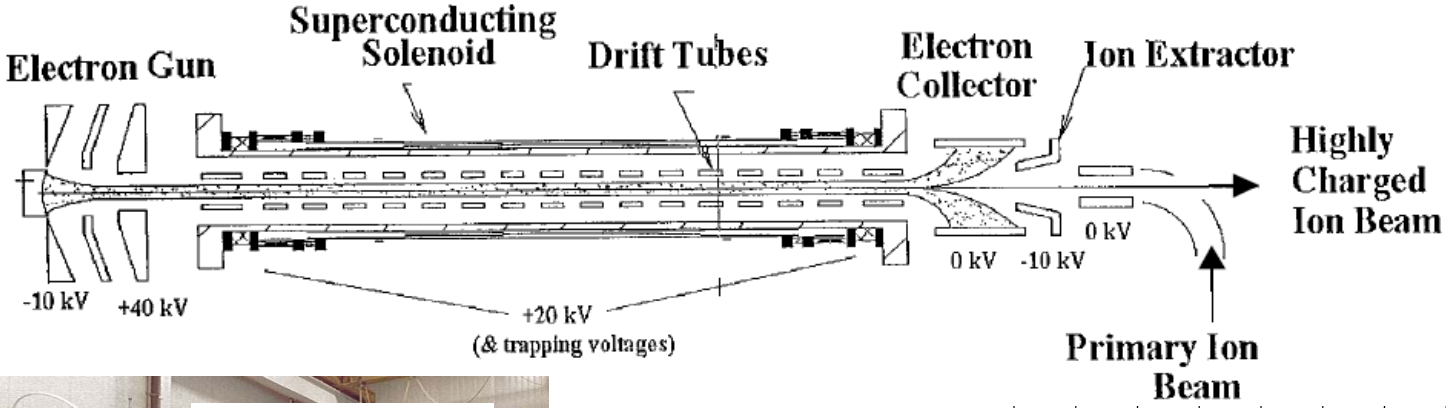
- Replace 1 - 4 RHIC bunches every AGS cycle, beam stays in RHIC only 3 - 7 min; ~ 2 - 3 more luminosity
- Needs modification of RHIC injection and extraction kickers and experiments need to stay on during continuous refill (likely ok, test desirable)

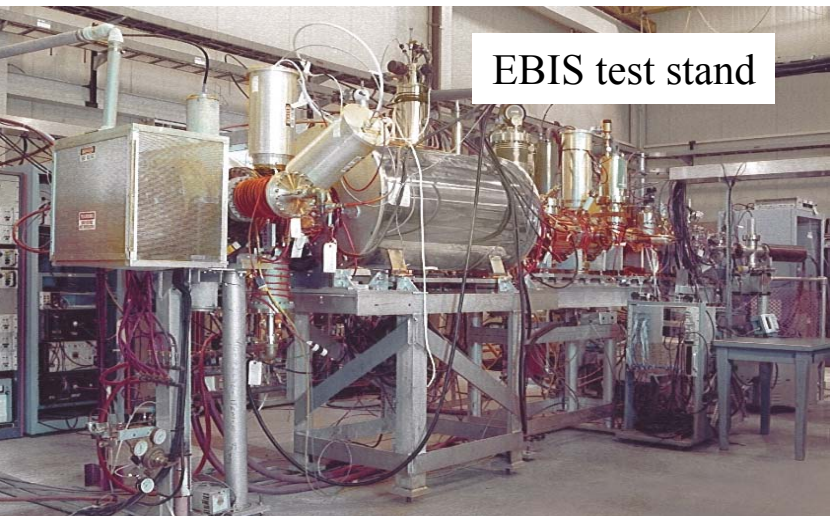
RHIC Upgrade Path

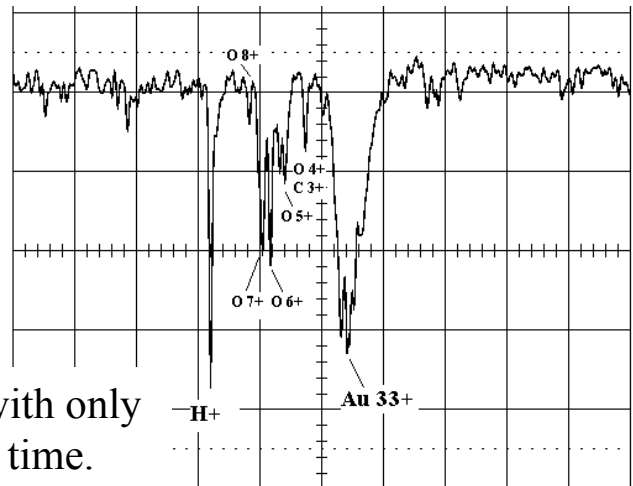
- Next 1 – 2 years: "enhanced RHIC luminosity"
- Next 3 – 4 years: additional × 5 luminosity upgrade:
  - 0.5 m betastar for Au – Au and p – p operation (in progress)
  - Stochastic cooling in RHIC of Au beams
  - New storage rf system in RHIC (56 MHz SRF cavity)
  - Electron lens in RHIC for beam-beam compensation (R&D)
- EBIS (low maintenance linac-based pre-injector; all species incl. U and polarized ^{3}He)
- eRHIC: high luminosity (1×10^{33} cm^{-2} s^{-1}) eA and pol. ep collider using 10 - 20 GeV electron driver, based on Energy Recovering Linac (ERL), and strong cooling of hadron beams

Electron Beam Ion Source (EBIS, ≥ 2010)

- New high brightness, high charge-state pulsed ion source, ideal as source for RHIC
- Produces beams of all ion species including noble gas ions, uranium (RHIC) and polarized He^3 (eRHIC)
- Achieved 1.7×10^9 Au^{33+} in 20 μs pulse with 8 A electron beam (60% neutralization)
- Construction schedule: FY2006 – 10

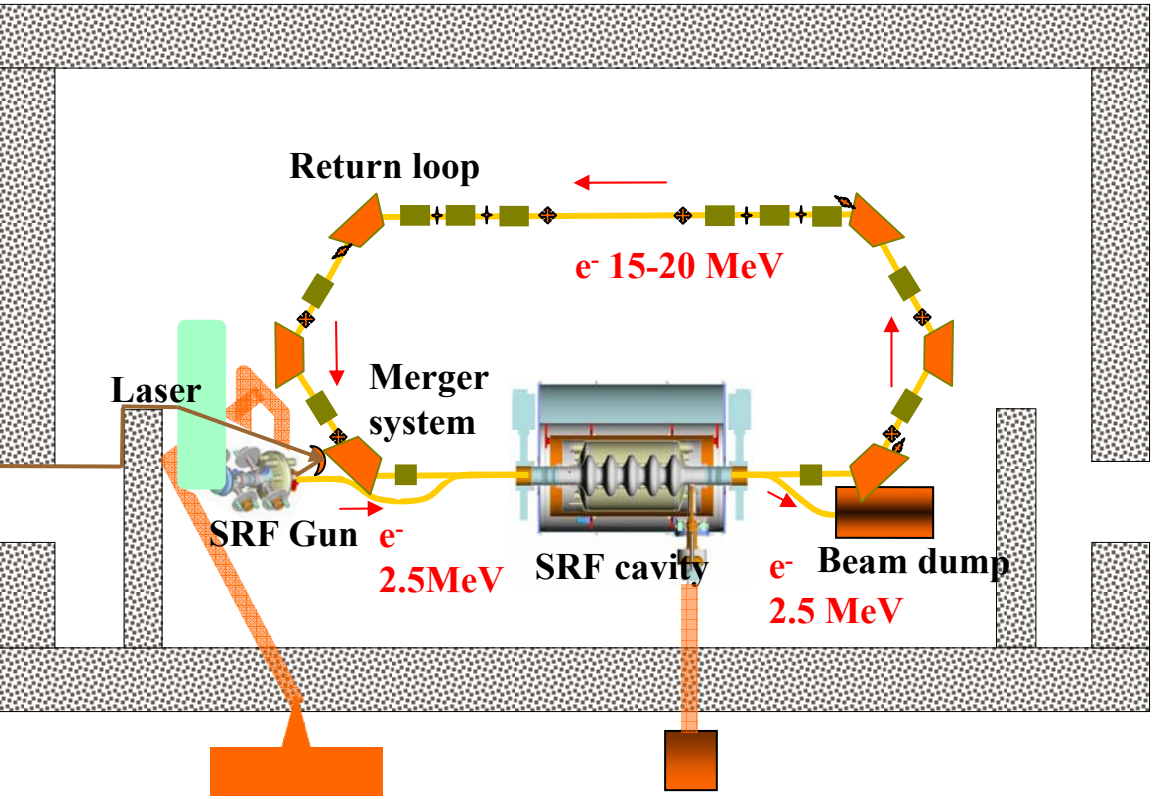






Gold charge state with only 40 ms confinement time.

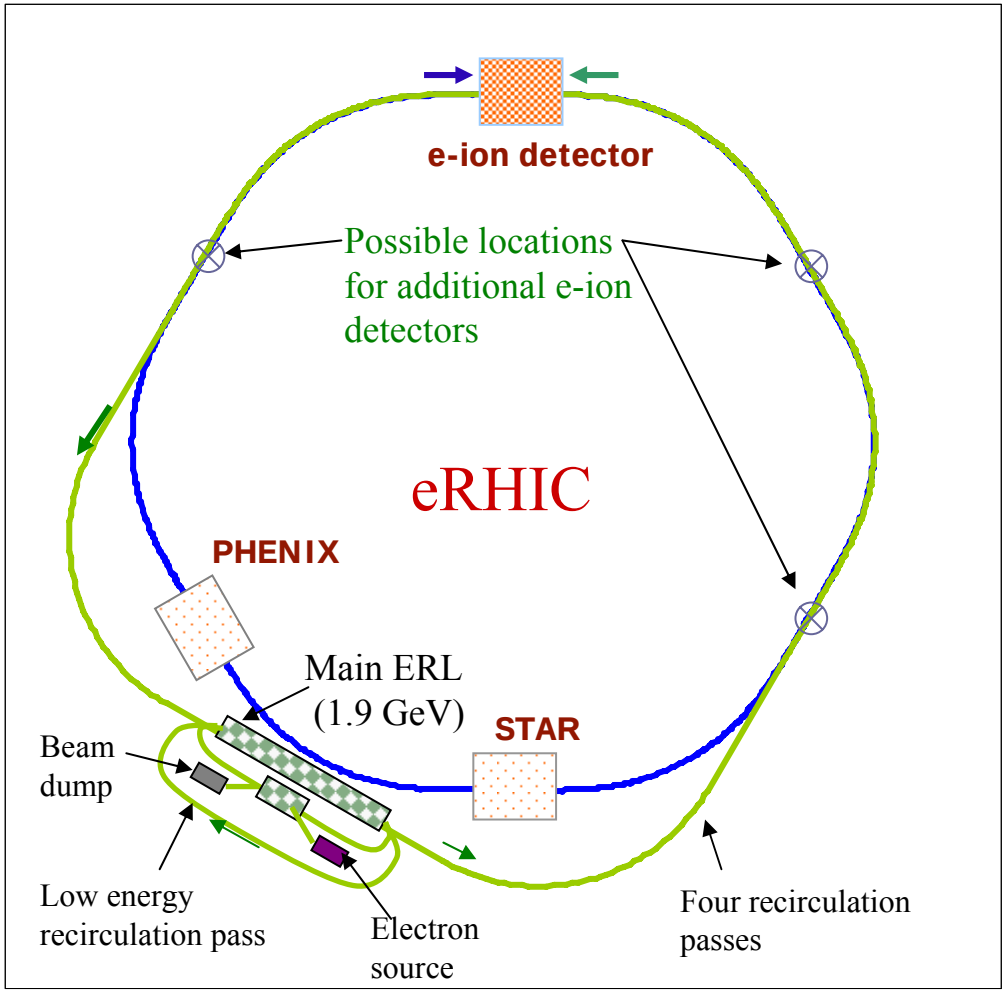
Energy Recovery Linac (ERL) Test Facility

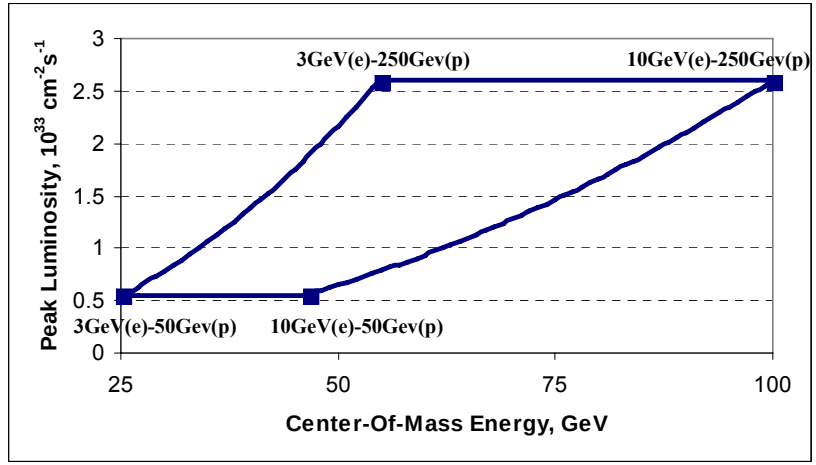


- test of high current (several hundred mA), high brightness ERL operation
- test of high current beam stability issues
- 5-cell cavity SRF ERL
- highly flexible lattice
- 704 MHz SRF gun test
- Start of the commissioning in 2009.

5 cell SRF cavity arrived in BNL in March 2008 .

ERL – based eRHIC Design

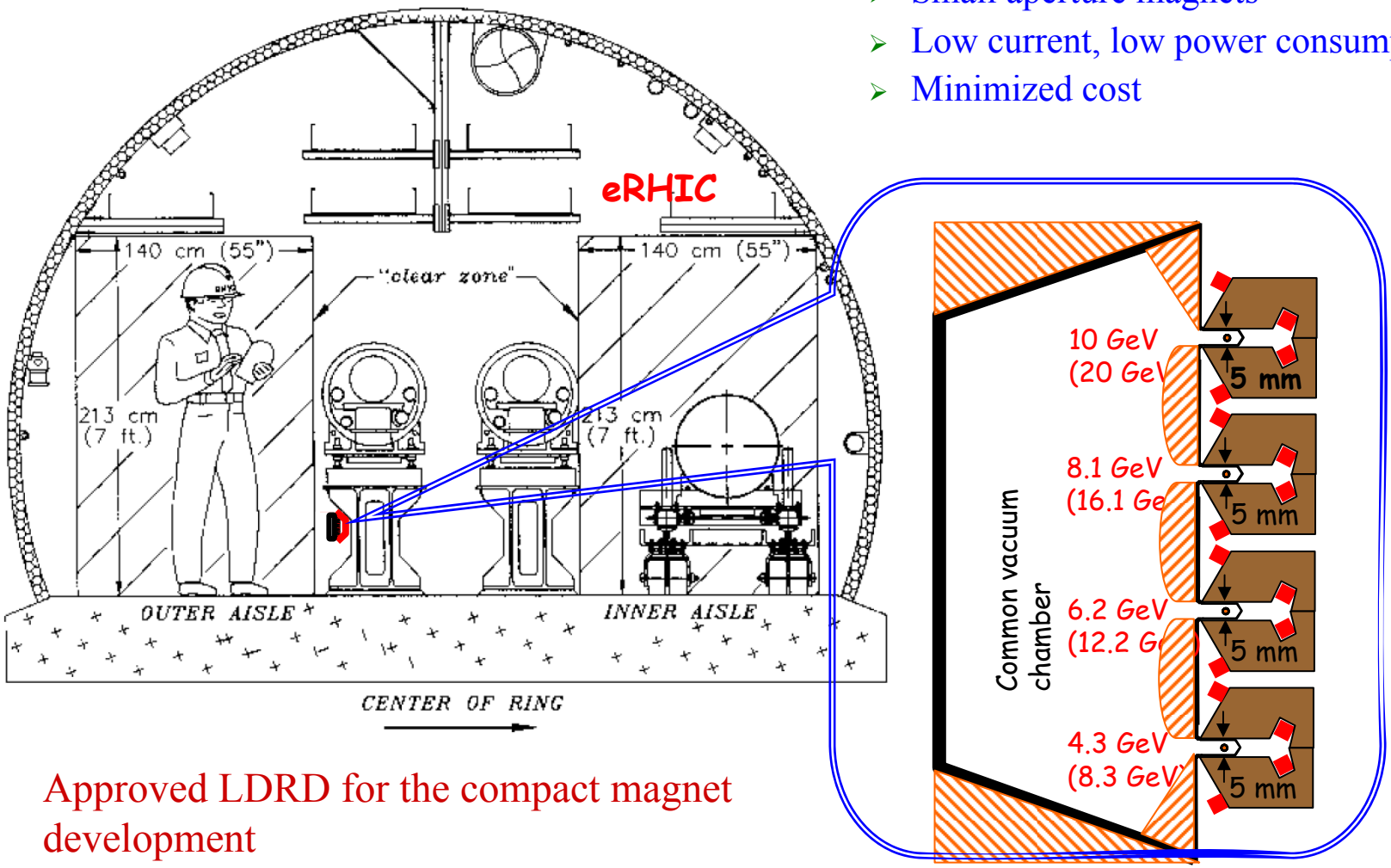




- 10 GeV electron design energy. Possible upgrade to 20 GeV by doubling main linac length.
- 5 recirculation passes (4 of them in the RHIC tunnel)
- Multiple electron-hadron interaction points (IPs) and detectors;
- Full polarization transparency at all energies for the electron beam;
- Ability to take full advantage of transverse cooling of the hadron beams;
- Possible options to include polarized positrons: compact storage ring; Compton backscattering; undulator-based. All options at lower luminosity.

Recirculation passes

- Separate recirculation loops
- Small aperture magnets
- Low current, low power consumption
- Minimized cost



Approved LDRD for the compact magnet development

BROOKHAVEN NATIONAL LABORATORY

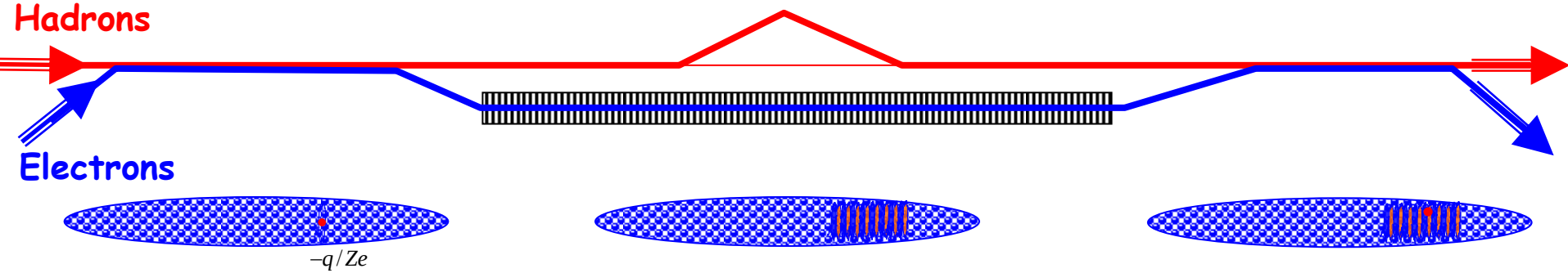
Coherent electron cooling

- Idea proposed by Y. Derbenev in 1980, novel scheme with full evaluation developed by V. Litvinenko
- Fast cooling of high energy hadron beams
- Made possible by high brightness electron beams and FEL technology
- ~ 20 minutes cooling time for 250 GeV protons → much reduced electron current, higher eRHIC luminosity
- Proof-of-principle demonstration possible in RHIC using test ERL.

Pick-up: electrostatic imprint of hadron charge distribution onto co-moving electron beam

Amplifier: Free Electron Laser (FEL) with gain of 100 -1000 amplifies density variations of electron beam, energy dependent delay of hadron beam

Kicker: electron beam corrects energy error of co-moving hadron beam through electrostatic interaction

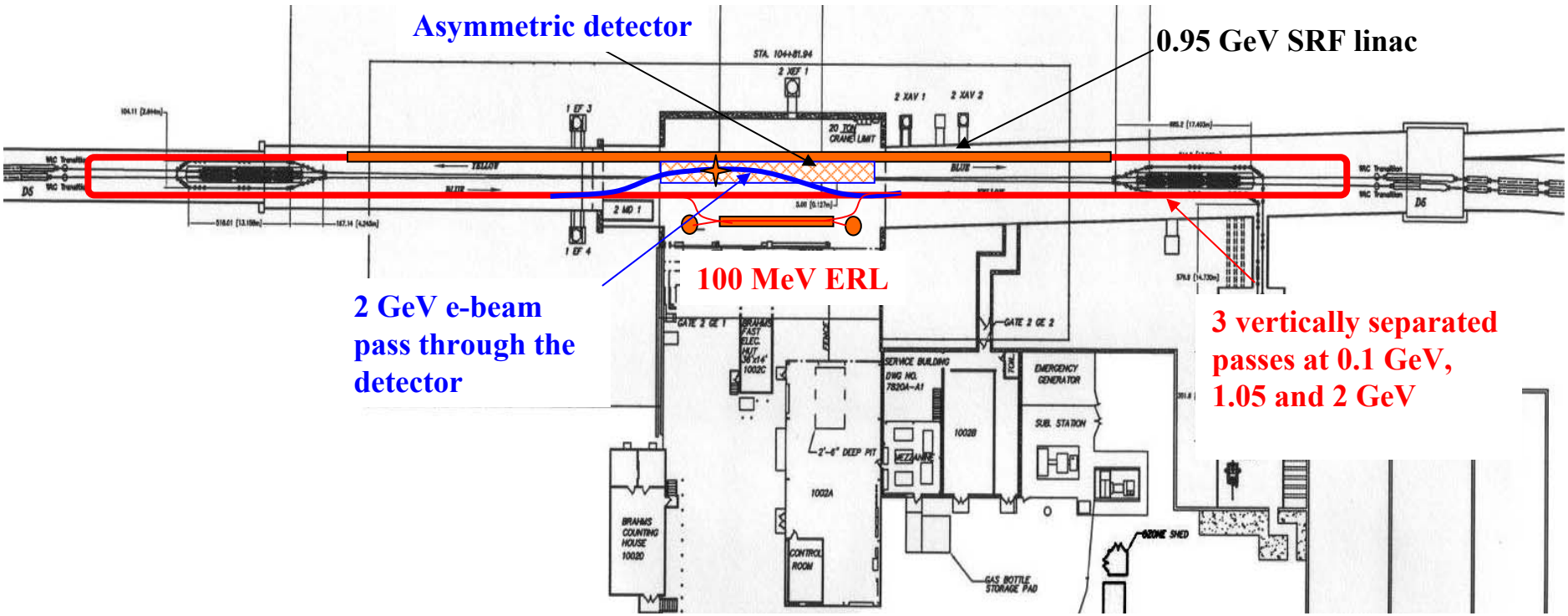


First stage of eRHIC: 2 GeV ERL inside RHIC tunnel @ IP2

Medium Energy Electron-Ion Collider (MEIC)

Located at IP2 (with a modest detector)

2 GeV e^- × 250 GeV p (45 GeV c.m.), L ~ 10^{32} cm^{-2} s^{-1}



Summary

Since 2000 RHIC has collided, at many different collision energies,

- Heavy and light ions
- Heavy on light on ions
- Polarized protons with 60 % beam polarization

Heavy ion luminosity exceeded enhanced luminosity goal

Successful test of Au collisions at very low energy (~ ½ normal injection energy)

Successful operation of longitudinal stochastic cooling

Future runs and upgrades:

- Factor 3 increase in proton luminosity with 70 % polarization
- High luminosity 250 x 250 GeV polarized proton run
- Uranium beams from EBIS
- × 5 luminosity upgrade [~ 40×10^{26} cm^{-2} s^{-1}]
- eRHIC (Medium energy electron ion collider, coherent electron cooling)